Severe Plastic Deformation (SPD) Using a Combination of Upsetting and Extrusion

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Abstract

Severe plastic deformation can be imparted to bulk materials using a combination of conventional metal forming processes such as upsetting and extrusion. Repetitive upsetting-extrusion (RUE) is one such process. Though the process imparts large strains and is capable of refining the grain size to submicron level, it imparts inhomogeneous deformation. To improve the homogeneity, it is proposed to combine these two processes; upsetting and extrusion in several ways. This combination manifests as processing routes. The proposed processing routes have been evaluated for their deformation homogeneity in order to identify an optimum processing route. The results obtained are presented and discussed here.

Keywords

Upsetting; Extrusion; SPD; RUE; Processing Routes

Introduction

There has been a considerable growth in the research and development of processes that are capable of imparting large plastic strain to materials. Though conventional metal forming processes such as rolling, extrusion, forging etc. can impart large strain; these processes alter the cross-section of the materials that are processed. As the cross-section is altered, further straining of the material becomes difficult (if not impossible) once a critical limit is reached. Further, most of these individual conventional forming processes follow a monotonic strain path that leads to a fibrous substructure that contains large amount of low angle boundaries (Valiev et al 2000, Alexander 2007, Azushima et al 2008). To overcome these issues, a variety of deformation processes has been developed ever since the pioneering work of Bridgman(Valiev et al 2000, Alexander 2007, Azushima et al 2008). These processes which are popularly known as severe plastic deformation (SPD) processes (Valiev et al 2000, Alexander 2007, Azushima et al 2008) can impart large strain to materials in either bulk or sheet form without altering their cross-section. The intrinsic nature or design of many of these processes permits variable strain paths that aid in refining the grain size to submicron (grain size: 100 nm to ≤1 μm) or even to nano level (≤100 nm). These ultrafine or nano grained materials exhibit superior strength and ductility, super plasticity at low temperatures and high strain rates, high wear resistance, high corrosion resistance and enhanced fatigue life (Zrnik et al 2008). A variety of SPD processes for processing bulk and sheet materials in either a batch or continuous mode is in vogue today [1-3]. The most popular ones are Equal Channel Angular Pressing (Segal 1981, Segal 1995, Segal 2002, Chen et al 2007, Balasundar et al 2009) High Pressure Torsion (Alexander et al 2008), Cyclic Extrusion Compression (Richert et al 1998, Rosochowski et al 2000, Richert et al 1998), Accumulative Roll Bonding (Saito et al 1999, Tsuji et al 1999), Repetitive Corrugation and Straightening (Hang 2004), Asymmetric rolling (Ji et al 2009, Ji et al 2007), Constrained Groove Pressing (Yang et al 2008, Shin et al 2002, Zrnik et al 2008). Though Cyclic Extrusion Compression (CEC) has been known for quite some time, processing of materials using such a process requires a bidirectional press which can apply sufficient amount of pressure at both ends. The scaling up potential of such a process is rather limited owing to the large variation in strain distribution imparted during the extrusion process and the large amount of back pressure which is required to ensure complete filling of the die cavity. Hu Lianxi et al (2006) used a combination of upsetting and extrusion to impart severe plastic deformation in a bulk aluminium alloy and established that the process is capable of producing ultrafine grains in bulk materials. This process used by Hu Lianxi et al (2006) known as Repetitive Upsetting-Extrusion (RUE) was originally invented by Aizawa et al (1999) to process powder materials for bulk mechanical alloying. Unlike CEC, RUE does not require back pressure to fill the die cavity. This implies that by using a suitable die design, the RUE process can be carried out on a unidirectional

press with conventional tooling as established by Balasundar et al (2011). Further, materials with larger dimensions can be readily processed using RUE. As the upsetting and extrusion ratio are kept at a minimum (1.5 and 2.0 respectively), better homogeneity can be expected when compared to CEC.

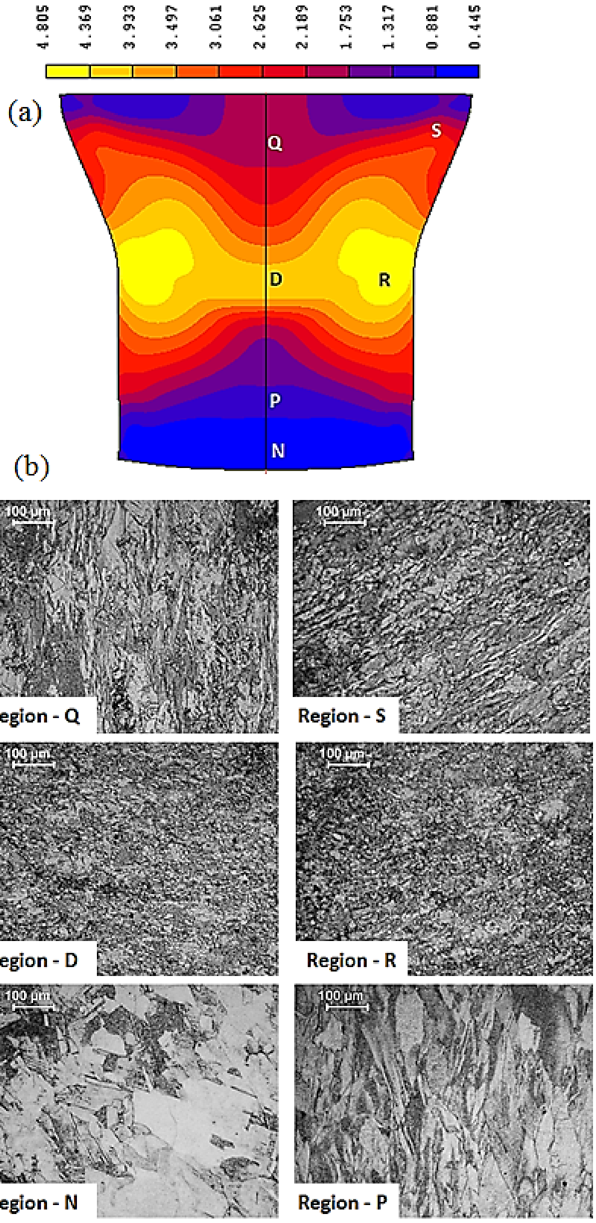

FIG. 1(a) EQUIVALENT STRAIN DISTRIBUTION AFTER 4 CYCLES OF RUE (b) MICROSTRUCTURES OBTAINED AT VARIOUS LOCATIONS IN THE COPPER SAMPLE SUBJECTED TO 4 RUE CYCLES DEPICTING INHOMOGENEOUS DEFORMATION

A detailed study on the deformation behaviour of commercial pure copper by Balasundar and Raghu (2010, 2011) revealed that the die design used by Aizawa et al (1999) to process powder materials, cannot be used for processing bulk solid materials as it imparts defects such as folds and axial holes during the upsetting and extrusion stage of subsequent RUE cycles. Balasundar et al (2010) established the critical conditions to avoid the formation of these defects and accordingly proposed a modified die design. Though the modified die design was found to be effective in avoiding defects even after a large number of RUE cycles [27], the deformation was found to be inhomogeneous due to the large strain gradients present across the cross-section of the work piece as shown in Fig. 1a. This large strain gradient results in inhomogeneous grain refinement as shown in Fig. 1b. Therefore, to improve the homogeneity of the process, the upsetting and extrusion processes are proposed to be combined in different ways. These possible combinations manifests as processing routes. Further, combining upsetting and extrusion in different ways would assist in providing varying strain paths for deformation, which would enhance grain refinement similar to ECAP.

The objective of the current work is two-fold; first of which is to propose possible combinations of upsetting and extrusion processes that can be used to impart severe deformation in bulk materials; while the other is to evaluate the proposed processing routes by carrying out Finite Element Analysis (FEA) and identify the optimum processing combination or route that provides better homogeneity.

Processing Routes

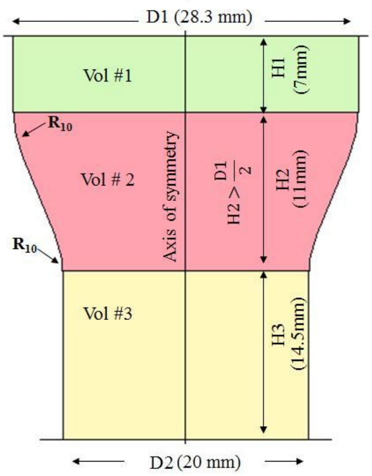

FIG. 2 MODIFIED DIE DESIGN FOR RUE AND REU PROCESSES

The repetitive process may begin with upsetting or extrusion. If the process is initiated with upsetting, it is known as repetitive upsetting-extrusion (RUE) as named by Hu Lianxi et al (2006) whereas it shall be called as repetitive extrusion-upsetting (REU) when it is initiated with extrusion. For both these processes, the modified die design established by Balasundar and Raghu (2010, 2011) can be used to avoid the axial hole and fold formation. The die cavity can be divided into

three regions each having a volume V_1, V_2, and V_3 respectively as shown in Fig 2. These volumes are designed in such a way that $V_1+V_2=V_2+V_3$. During upsetting the work piece fills the volume $V_u=V_1+V_2$ whereas it fills the volume $V_e=V_2+V_3$ during extrusion. Volume of the work piece (V_w) is therefore given by $V_w= (V_1 + V_2) = (V_2 + V_3)$.

Though the volume of the work piece (V_w) that is required to carry out RUE and REU experiments would be the same, the aspect ratio (height/diameter) of the starting work piece would be different. REU process would require a lower aspect ratio starting work piece when compared to the RUE process. If one decides that the work piece has to be removed from the die cavity only after a predetermined number of upsetting and extrusion cycles (or vice versa) are completed, then there would be a large strain gradient in the work piece as reported by Balasundar et al (2012, 2011) for RUE process.

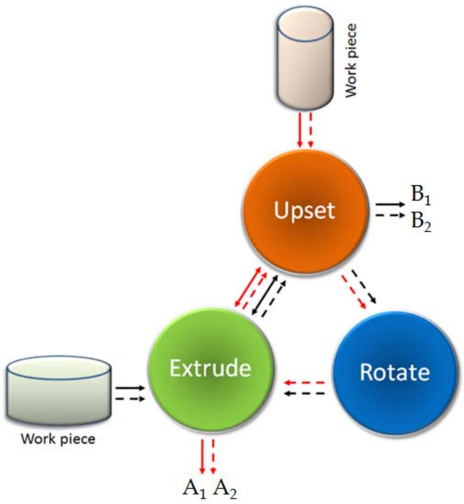

FIG. 3 POSSIBLE PROCESSING ROUTES

To overcome these difficulties and to ensure better homogeneity in strain distribution, it is proposed to introduce a rotation step after the upsetting stage of both RUE and REU process. The rotation of the work piece about its axis after the upsetting stage is expected not only to provide better homogeneity but also to vary the strain path. It has already been well established that a change in the strain path helps in refining the microstructure at a faster rate (Valiev et al 2000, Alexander 2007, Azushima et al 2008). There are four possible processing routes that can be used to impart severe plastic deformation in bulk materials using either RUE or REU. These four processing routes are summarized in Fig. 3. The processing routes identified here are for processing cylindrical samples i.e., for axisymmetric conditions. The axisymmetric condition restricts the rotation of the work piece to only one direction i.e., about the work piece axis. However, the RUE or REU processes can also be carried out under plain strain conditions using square cross-sectioned work piece. The plane strain RUE or REU process would result in additional rotational degrees of freedom. The work piece in such cases can be rotated along the work piece axis similar to that reported for equal channel angular extrusion/ pressing (ECAE/P) process. Considering the axisymmetric case, the repetitive process is denoted as 'A' when initiated with upsetting and as 'B' when initiated with extrusion. Further under each category, the following routes can be readily visualized.

Repetitive Upsetting-Extrusion (RUE) Process (A)

- **Route A_1:** The processing route comprises upsetting followed by extrusion. Route A_1 is similar to that which has been reported by Aizawa et al (1999), Hu Lianxi et al (2006) and Balasundar et al (2010, 2011, 2012)
- **Route A_2:** In this processing route, the work piece would be upset, then rotated by 180° about the upsetting axis and extruded. Thus a cycle of RUE route A_2 would be upset-rotate-extrude.

Repetitive Extrusion-Upsetting (REU) Process (B)

- **Route B_1:** Work piece would be subjected to repeated extrusion and upsetting. As Route B_1 begins with extrusion, the aspect ratio of the starting work piece required to fill the extrusion and upsetting volumes would be lower.
- **Route B_2:** The low aspect ratio work piece would first be extruded and then upsetted. However, the upsettedwork piece in route B_2 would be rotated by 180° about its upsetting axis before it is extruded again. Thus a cycle in route B_2 comprises extrusion, upsetting and rotation.

In case of route B_1 and B_2, the upset sample may be removed from the die cavity and subjected to a final upsetting in order to regain the original work piece dimension. Though the work piece can be extruded completely using a dummy block after desired number of processing cycles through RUE routes A_1 and A_2, the formation of funnel/pipe cannot be avoided. This pipe/funnel formation would lead to wastage of the processed material and hence, complete

extrusion of the material after processing via RUE routes A_1 and A_2 is not recommended.

Finite Element Analysis

In order to evaluate the RUE and REU processing routes, the deformation behaviour of commercial pure copper (CP Cu) was simulated using MSc Marc 2010r1. As both the shape of thework piece and the nature of loading are symmetrical about the sample axis for both RUE and REU processes, an axisymmetric rigid plastic finite element model as shown in Fig. 4 was used to reduce computation time. The work piece was assumed to be deformable and meshed with 4-node isoparametric axisymmetric elements. Though the initial mesh was coarse (3000 elements), during deformation the mesh was refined by automatic remeshing to accommodate large strains. The number of elements was increased during the first remeshing operation and maintained constant throughout the simulation. From the mesh sensitivity analysis, 7500 elements were found to be sufficient to model the deformation behaviour reliably. The constitutive relationship (σ=344.5 $\varepsilon^{0.21}$ where, σ and ε are flow stress and equivalent plastic strain respectively) established for Cu by Kundu et al (2008) was used to carry out the axisymmetric rigid plastic finite element analysis. The die wall, dies and punch were assumed to be rigid. For the analysis, a coulomb friction coefficient of 0.05 was assumed between the work piece and tools.

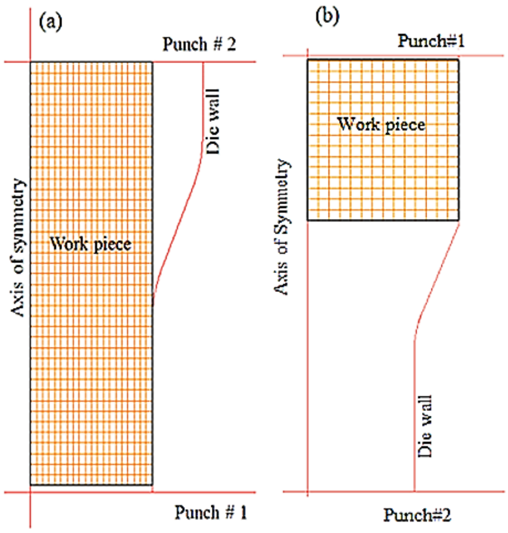

FIG. 4 AXISYMMETRIC FINITE ELEMENT MODEL TO SIMULATE THE (a) RUE AND (b) REU PROCESSING ROUTES

To simulate the deformation behaviour of CP Cu (20 mm diameter by 32 mm length) through route A_1, the die wall and punch#2 were assumed to be stationary (i.e., punch#2 acts as a stationary upsetting die) by imposing zero displacement boundary conditions. Punch#1 was assigned with a upward displacement, the velocity (constant punch velocity of 1 mm/sec was used for deformation) of which was controlled by using a control file that contains information on the speed, time required, number of sub-steps to be taken to achieve the specified deformation. After upsetting, punch#1 was retracted back to its original position. A constant punch velocity of 5 mm/sec was used to retract the punch. During extrusion, the die wall and punch#1 were assumed to be stationary. Punch#2 was assumed to move and extrude the upsettedwork piece. Once the work piece was extruded, punch#2 was retracted back to its original position. The above procedure was repeated four times to simulate 4 RUE cycles. A similar procedure was used to simulate Route B_1.

In order to simulate the processing routes A_2 and B_2, which involves rotation of the work piece about its axis, an additional step of work piece rotation after upsetting was incorporated in the abovementioned procedure. Further, in case of route B_1 and B_2, the geometry of the work piece was restored to its original dimension by introducing an additional upsetting step after 4 cycles.

Results and Discussions

Deformation Behaviour and Strain Distribution

The equivalent plastic strain obtained from the finite element analysis after 4 cycles of processing through various RUE and REU routes is shown in Fig. 5a-d. It can be seen that in case of route A_1, the material experiences maximum strain at the intersection of the die cavity volume V_2 and V_3. The Bottom portion of the sample experiences very less strain. This is because the bottom portion of the material does not experience much strain either during the upsetting or extrusion stage of RUE cycle through route A_1 as explained below. The deformation behaviour of the work piece during the upsetting stage of first RUE cycle through route A_1 is shown in Fig. 6a-d. As the work piece is pushed in to upsetting volume V_u where V_u= V_2+V_1 as shown in Fig. 6a, punch#2 acts as an upsetting die and restricts the movement of work piece along the vertical direction, this causes the compression of flow lines along the axis of symmetry (region-D). As the vertical movement is restricted and punch#1 is still pushing the work piece in to V_u, the work piece starts to flow along the horizontal direction to fill the die cavity. This horizontal flow of work piece to fill V_u causes the

horizontal and vertical flow lines to curve. Further, the horizontal flow lines were found to be in convex shape below region-D. As a plane of work piece is pushed in to the upsetting volume, the work piece material adjacent to the die wall starts to flow in horizontal direction whereas the work piece material at the center or at the axis of symmetry first moves along the vertical direction and then starts to flow along the horizontal direction. This variation in deformation behaviour can be attributed to the shape of vol#2 which causes the horizontal flow lines to assume a convex shape. It can also be seen from Fig. 6a-c that during upsetting, a part of the work piece still remains in vol#3. Due to the constraint imposed by the die wall, this portion of the work piece in vol#3 does not experience any deformation till it enters vol#2. As the last part of the work piece is pushed in to the upsetting volume V_u by punch#1 (along the vertical direction), then it displaces the adjacent material to flow in horizontal direction to fill the die cavity. This inverted U-shaped region of the work piece which enters V_u during the final stage of upsetting does not experience any deformation. The undeformed mesh or flow lines in this inverted U-shaped region (delineated by YY′ in Fig. 6b-d substantiates the fact that this region of work piece does not experience any deformation.

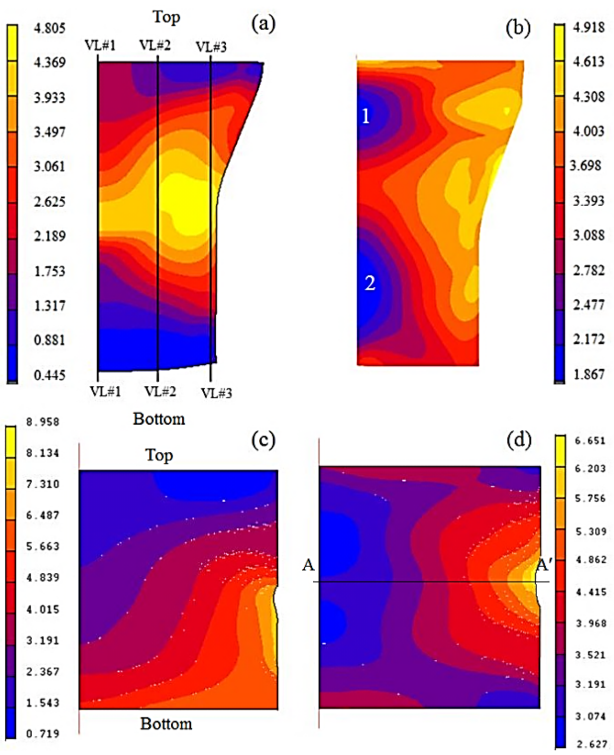

FIG. 5 EQUIVALENT PLASTIC STRAIN DISTRIBUTION OBTAINED AFTER 4 CYCLES OF PROCESSING THROUGH (a) RUE ROUTE A1 (b) RUE ROUTE A2 (c) REU ROUTE B1 (d) REU ROUTE B2

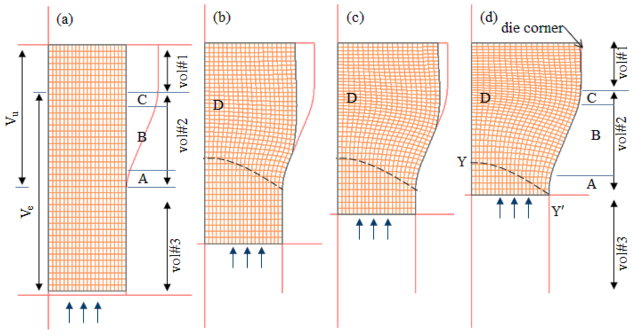

FIG. 6(a-d) DEFORMATION BEHAVIOUR DURING THE UPSETTING STAGE OF FIRST RUE CYCLE VIA ROUTE A1

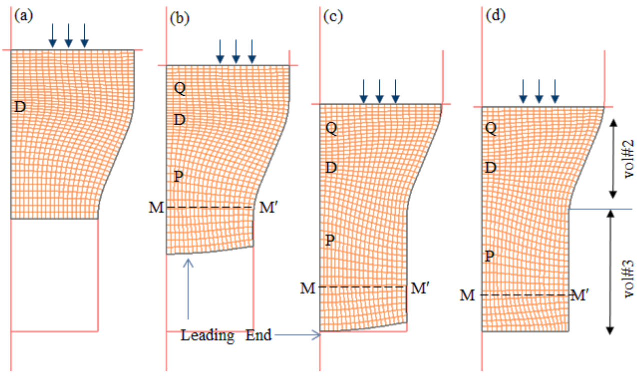

FIG. 7(a-d) DEFORMATION BEHAVIOUR DURING THE EXTRUSION STAGE OF FIRST RUE CYCLE VIA ROUTE A1

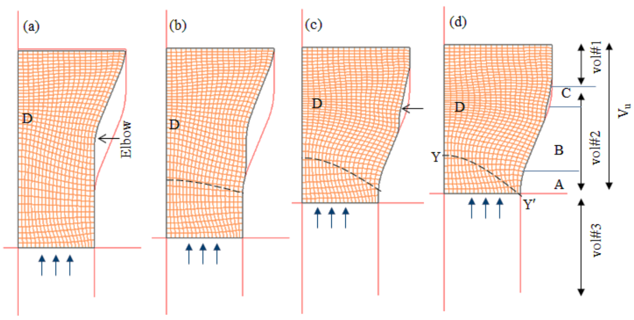

FIG. 8(a-d) DEFORMATION BEHAVIOUR UPSETTING STAGE OF SECOND RUE CYCLE THROUGH ROUTE A1

The deformation behaviour of the upsetted sample during the extrusion stage of first RUE cycle is shown in Fig. 7a-d. As the upset material is extruded by punch#2, the work piece exits vol#2 and enters vol#3. Due to the presence of friction between the work piece and the die wall, the work piece has least resistance to deformation along the axis of symmetry and hence the leading end of the work piece extrudes with a concave shape as shown in Fig. 7a-c. Punch#1 restricts the vertical movement of the leading end and assists in filling up the die completely. It can be noted that the die corners are filled only at the final stages of extrusion. Based on the orientation of horizontal flow lines, the extruded sample can be divided into three regions–P, D and Q as shown in Fig. 7b-d. The vol#2 region which acts as deformation zone during extrusion can be divided into three regions–A, B and C

as shown in Fig. 6d. In region B, the diameter varies linearly whereas nonlinearly in region A and C due to the fillet radii provided. However, the nonlinear variation of the work piece (or the die) diameter in region-A and C can be considered marigal since a fillet radius of only 10 mm was provided. During extrusion, till portion of work piece which filled the region-A of Vol#2 during upsetting is extruded, the horizontal flow lines are oriented towards the extrusion direction (Fig. 8b-d).

When the work piece that filled region-B of vol#2 during upsetting is extruded, the horizontal flow lines are oriented opposite to the extrusion direction. As the diameter of the work piece is reduced during extrusion, there is a flow of material from the rim to the center or axis of symmetry to maintain a constant volume. This inward movement of the material causes a gradual increase in the mesh height and hence increases the convexity of the horizontal flow line. The elements with reduced height and increased width at the rim and vice versa at the center concur well with the above statement (region-P in Fig. 7b-d). Further, as the diameter of the work piece material that filled region-B of vol#2 varies linearly, the diameter and hence the volume of the work piece that tries to exit the deformation zone during extrusion also increase. This increase in volume manifests in further increasing the convexity or orientation of the horizontal flow. When the work piece material that filled vol#1 during upsetting enters and fills the deformation zone (vol#2) during extrusion, the horizontal flow lines are oriented again towards the extrusion direction (region-Q). This is because only the rim portion of the material experiences deformation. It can also be seen that, in the extruded work piece (Fig. 7b-d), region-D where the mesh was compressed together during upsetting is still present with a marginal increase in the mesh height due to extrusion.

During the upsetting stage of the second RUE cycle, the truncated wedge shaped work piece geometry obtained at the end of the first RUE cycle becomes the starting work piece. Due to the shape of the work piece, it can be seen that the top region of vol#1 (i.e., region adjacent to punch#1) is filled even before the beginning of the upsetting process as shown in Fig. 8a. The deformation behaviour of the work piece during the upsetting stage of the second RUE cycle (Fig. 8a-d) is quite different to that observed during the upsetting stage of the first upsetting cycle (Fig. 6a-d). This difference in the deformation pattern can be attributed to the difference in the work piece geometry. During the upsetting stage of the second cycle, the elbow region present in the work piece hinders the smooth deformation of the work piece. As the elbow region offers resistance to deformation (i.e., acts as a virtual base), the work piece below this region starts to fill the die cavity by flowing along the horizontal or lateral direction. This causes further waviness in the vertical flow lines and compression in the mesh height at region-D. As deformation progresses, the material at the elbow region also deforms and flows along the horizontal direction to fill the die cavity (V_u). It can also be noted that the bottom portion of the work piece (MM′) still does not experience any deformation, and the same is true for the upsetting stage of the second RUE cycle. The deformation behaviour of the work piece during the extrusion stage of second RUE cycle through route A_1 and subsequent cycles are similar to that as explained above except for the increases in the intensity of deformation at region-D and the waviness of the flowlines caused due to the presence of the elbow region.

In case of RUE route A_2, the work piece is rotated after upsetting (i.e. Route A_2: upset – rotate –extrude). As the work piece is rotated, the bottom region that had experienced very less deformation (Region YY′ in Fig. 6) during upsetting becomes the top portion during extrusion and vice versa. As this rotated work piece is extruded, the top portion of the material (originally bottom region) experiences deformation. This extruded material is then upsetted to commence the second RUE cycle of route A_2. During the upsetting stage of the second RUE cycle through route A_2, the bottom portion of the work piece (originally top portion) experiences very less deformation as explained earlier. This deformation pattern is repeated during successive or subsequent cycles of pressing which manifests in two relatively less strained regions (Region 1 & 2 in Fig. 5b) in the work piece. However, it can be noted that the minimum strain observed after 4 cycles is much higher in the sample deformed using route A_2 when compared to route A_1.

The deformation pattern and equivalent plastic strain distribution in the sample after the first REU cycle through route B_1 is shown in Fig. 9a-c. As route B_1 is initiated with extrusion, the bottom portion of the work piece experiences deformation during the extrusion stage. Further, as the work piece dimensions are resorted during the upsetting stage, some amount of strain is imparted to the bottom region of the material. The top portion of the work piece does not experience much deformation as it never passes

through the deformation zone (i.e., volume V_2) during extrusion (Fig. 9a). As the diameter of this top portion does not get reduced during extrusion, it does not experience much strain during the upsetting stage as well. Hence, it can be seen that at the end of 4 REU cycles through route B_1 (Fig. 5c), the bottom portion of the material has experienced relatively large strain while the top portion of the work piece experiences less strain.

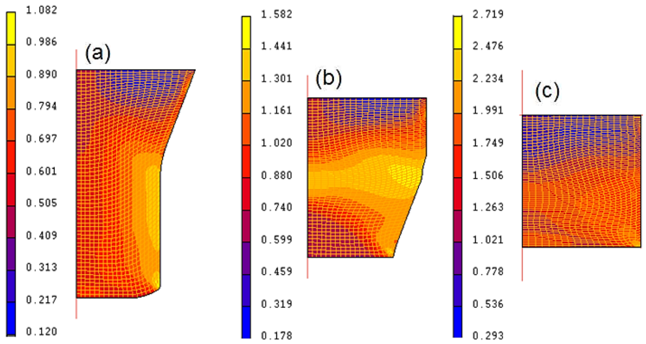

FIG. 9 DEFORMATION PATTERN AND EQUIVALENT STRAIN DISTRIBUTION DURING (a) EXTRUSION STAGE (b) UPSETTING STAGE (c) FINAL UPSETTING STAGE OF THE FIRST REU CYCLE VIA ROUTE B1

In case of route B_2, the work piece is rotated after the first REU cycle, then the top portion of the work piece becomes the bottom portion and vice versa during the second REU cycle. During the second REU cycle through route B_2, the original top portion (bottom portion during second REU cycle) of the work piece receives large deformation both during extrusion and upsetting stage. This implies that the portion of the material which experiences less deformation during the first cycle through route B_2, experiences large deformation in the second cycle and vice versa. This cyclic deformation pattern is expected to improve the strain distribution leading to better homogeneity. The symmetric distribution of strain (about the horizontal line AA′ in Fig. 5d) in the sample subjected to 4 REU cycles through route B_2 concurswell with the abovementioned statement.

Average Equivalent Plastic Strain

To gain further understanding on the deformation behaviour, the strain distribution along the three vertical lines (VL#1, 2 and 3 as shown in Fig. 5a) were extracted from the samples subjected to various processing routes. The variation of equivalent plastic strain along the vertical line VL#2 (Top to Bottom) after 4 cycles of deformation through various processing routes is shown in Fig. 10. As the aspect ratio of the RUE and REU samples are different, the height of the sample was normalised between 0 to 1 using the relation (X-Xmin)/(Xmax-Xmin), where X is the actual distance (mm) of the node from the top surface of the work piece, Xmin = 0, Xmax = 25 mm for RUE and 15 mm for REU processing routes.

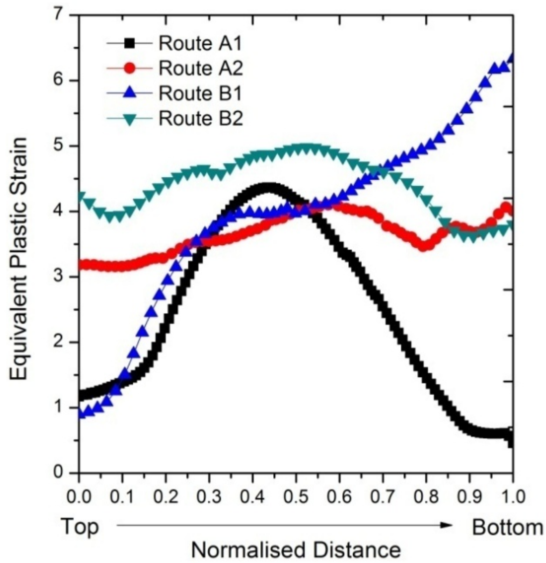

FIG. 10 VARIATION OF EQUIVALENT PLASTIC STRAIN ALONG VL#2 AFTER 4 CYCLES FOR DIFFERENT PROCESSING ROUTES

It can be seen that, in case of route A_1, the maximum equivalent plastic strain ($\varepsilon = 4.36$) is observed at the location that corresponds to the elbow region where vol#2 and Vol#3 intersect. In case of route B_1, the equivalent plastic strain increases continuously from top to bottom. In case of route A_2 and B_2 which involves rotation of the work piece, the variation between the maximum and minimum value of equivalent plastic strain is considerally less when compared to the processing routes that do not involve rotation. Usning the equivalent plastic strain obtained along the three vertical lines, the average strain across the sample cross-section was evaluated after each cycle of RUE and REU processing. The average strain was then compared with the analytical strain calculated using the following expression:

$$Strain\ (\varepsilon) = 4.N.\ln\left(\frac{d_1}{d_2}\right). \qquad (1)$$

where N is the number of cycles and d_1, d_2 are the diameters of the volumes V_1 and V_3 respectively. Substituting this strain in the Von-Mises equation gives the equivalent plastic strain [24, 28]. It can be seen from Fig. 11 that the average strain imparted by REU through the routes B_1 and B_2 is comparable to the analytical strain, whereas the average strains imparted by RUE via the routes A_1 and A_2 are much less than the analytical strain. Therefore, REU processing routes B_1 and B_2 which impart a higher average strain per cycle are better routes when compared to RUE processing routes A_1 and A_2.

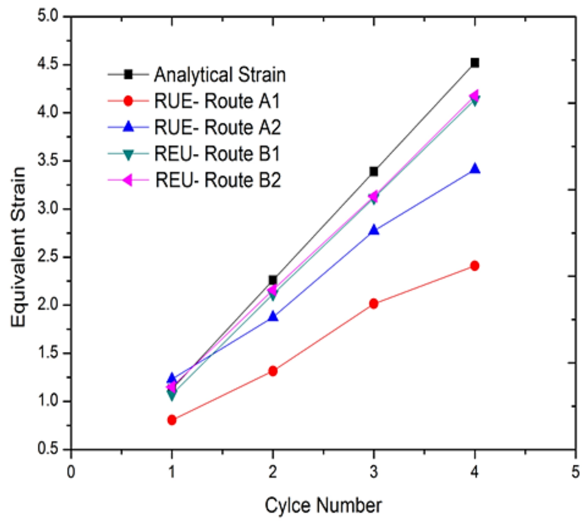

FIG. 11 AVERAGE STRAIN PER CYCLE IMPOSED BY VARIOUS RUE AND REU PROCESSING ROUTES

Deformation Homogeneity

The homogeneity of a process or processing route is generally evaluated using an inhomogeneity index (Balasundar et al 2011). The degree of strain inhomogeneity (Balasundar et al 2010, 2012) can be estimated using the following equation

$$CV\varepsilon_p = \frac{\text{Stdev}\ \varepsilon_p}{\text{Avg.}\varepsilon_p} \tag{2}$$

In the expression $CV\varepsilon_p$ represents the coefficient of variance of equivalent plastic strain (also called as the inhomogeneity index), $\text{Stdev}\varepsilon_p$ is the standard deviation of equivalent plastic strain and $\text{Avg.}\varepsilon_p$ is the average total equivalent plastic strain along a cross-section. As the variation of equivalent plastic strain across the work piece cross-section decreases, the standard deviation of equivalent plastic strain decreases. With decreasing standard deviation and increasing value of average strain, the coefficient of variance or inhomogeneity index decreases implying a more uniform distribution of equivalent plastic strain across the work piececross-section. Using the strain obtained along the three vertical lines (Fig. 6a), the average $CV\varepsilon_p$ of RUE and REU processing routes were estimated for each cycle and are shown in Fig. 12. It can be seen that $CV\varepsilon_p$ initially increases from the first to second cycle and thereafter it remains practically constant in case of RUE route A_1 and REU route B_1. Whereas in case of RUE route A_2 and REU route B_2, the inhomogeneity initially decreases from cycle one to two and thereafter it remains constant. It can also be observed that for any given cycle, RUE route A_2 and REU route B_2 have lower inhomogeneity index when compared to the routes A_1 and B_1. This implies that the rotation of the work piece during subsequent processing stages or cycle aids in achieving better homogeneity. Therefore with regard to homogeneity, RUE route A_2 and REU route B_2 are better processing routes.

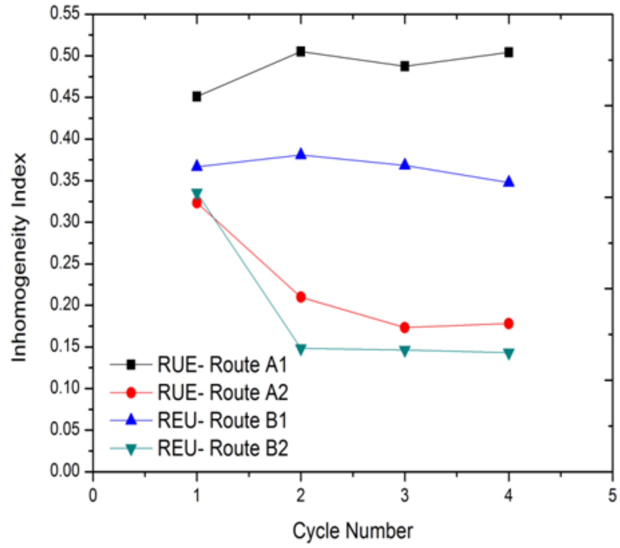

FIG. 12 VARIATION OF INHOMOGENEITY INDEX FOR VARIOUS RUE AND REU PROCESSING ROUTES

Conclusions

The following can be concluded based on the evaluation of the proposed RUE and REU processing routes;

(1) With respect to the strain imparted, REU processing routes B_1 and B_2 impart higher average strain per cycle which is close to the analytical strain.

(2) With respect to homogeneity, processing routes that involve rotation of the work piece after upsetting (RUE route A_2 and REU route B_2) impart better homogeneity when compared to the processing routes which donot involve rotation.

(3) It can therefore be concluded that REU route B_2 (Extrude-Upset–Rotate) provides a higher average strain per cycle and better homogeneity and therefore it can be considered as the optimum processing route.

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